. This study was completed in 1980.

File G-10
CREEP

INVESTIGATION OF

CREEP BEHAVIOR OF THE GLASS FIBER REINFORCED COMPOSITE MAGNET STAND-OFFS

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CREEP BEHAVIOR OF THE GLASS FIBER REINFORCED COMPOSITE MAGNET STAND-OFFS

INTRODUCTION AND BACKGROUND

The energy doubler project at Fermi National Accelerator Laboratory is considering employing glass fiber reinforced polymers (GFRP) as magnet stand-offs in the cryogenic particle accelerator. The use of fiberglass supports stems from the excellent insulating and strength properties of these types of composites. Upon magnet assembly, these supports are compressively loaded at room temperature and stored for a period of time which may range from one month to a number of years. Once the magnet is placed into service, the environmental temperature of the composite is dropped from 300°K to 78°K and subsequently to 4°K, which is the operating temperature of the cryostat. The GFRP stand-offs, as a result, experience a total temperature excursion from room temperature to 4°K while under a predetermined initial compressive assembly load. The main role of the stand-offs is to maintain alignment to the inner magnet core while allowing very little heat flow into the 4°K environment. If alignment is lost, the magnet loses accurate particle guidance and must be replaced. The stand-offs, therefore, must remain structurally rigid not exhibiting extensive creep at room temperature storage or at cryogenic operation.

In order to select a composite which is best suited for this cryogenic application, an accurate prediction of the strain response of GFRP across wide temperature ranges must be achieved. Since most GFRP exhibits near linear stress-strain response from room temperature to 4°K, it has been often erroneously assumed that these materials are elastic, having a Young's modulus which is highly temperature dependent. Accordingly, this assumption leads to gross miscalculations of strain during the temperature excursion while the material is under stress.

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Since fiberglass is empirically known to creep significantly throughout the temperature spectrum with creep rates decreasing with decreasing temperature, an accurate strain accounting method must be employed to separate creep and elastic strains while stresses are present in order to precisely predict total strain. Moreover, accounting for total strain components as being elastic or creep provides for an accurate determination of total strain over wide temperature excursions and gives an explanation for the immoderate temperature sensitivity of the slope of the stress-strain curve.

MATERIALS TESTED

Three materials were tested for room temperature creep response in a constant load creep fixture shown in Figure 1. The specimens are designated as G10, G11 and a laminate which is composed of alternating steel shim-fiberglass sandwich arrangement. All specimen dimensions are shown in Figure 2.

THEORY

The equation for total strain under constant load is:

$$\varepsilon = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} \quad t^n$$

where E_0 is the modulus at 4°K,

E_1 and n are empirical constants,

σ is the applied stress and

t is the elapsed time in minutes.

This equation accounts for both elastic and time dependent strains (creep strain) over time. In order to evaluate the material parameters in the above equation, constant load tests were performed measuring strain extensions over time. It is noted that during initial loading to constant stress, the GFRP strain response exhibits two components of strain:

- The elastic portion dictated by the modulus at 4°K.

- The creep portion dictated by the creep behavior of the GFRP at the test temperature.

Together these components define the stress-strain response of GFRP which exhibits a near linear relationship for stress as a function of strain. For the time period where a load is being ramped to a constant stress value, the total component of accumulated creep strain may be mathematically described as:

$$\varepsilon_{creep} = \frac{\sigma}{E_{room}} - \frac{\sigma}{E_0}$$

not general (only valid for time of loading)

where E_{room} is the slope of the stress-strain curve at room temperature.

This component of creep must be accounted for in all subsequent data taken over time in order to effectively characterize the material. If this component is ignored, (i.e., time is taken as 0 after the constant stress value is achieved), any creep measurements made employing this offset "time base" will be erroneous. Plotting the creep data obtained in the manner described on log-log paper results in a straight line of slope n and a unit time intercept equal to $\frac{\sigma}{E_1}$.

RESULTS AND DISCUSSION

General

The constant strss creep tests performed determine the empirical constants for the GFRP and the laminate as shown in Table 1. It must be noted that the constant E_0 was assumed for each individual material and was not measured. In order to improve the accuracy of the results, it is suggested that the modulus of the GFRP and the laminate be measured at a low temperature at or near 4°K. Nonetheless, the materials may be comparatively ranked in order of creep resistance and these are as follows:

- The laminate exhibits maximum creep resistance over time as shown by the material parameters in Table 1 and the graphs in Figure 8.

- The G11 material exhibits somewhat less creep resistance than the laminate as shown in Table 1 and Figure No's. 6 and 7.

- Lastly, the least creep resistance is exhibited by G10 as shown in Figure No's. 3, 4 and 5.

It is noted as a general result, that none of the materials studied exhibit very low creep extension as is dictated by the cryogenic application.

Creep Compliance and Relaxation Modulus

With the creep and elastic strain components described in this manner and with the value of the exponent n being small (less than 0.1), a stress relaxation analysis may be performed using constant stress creep data. This analysis proceeds as follows:

- Using the constant stress creep equation,

$$\varepsilon = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} t^n$$

and factoring it into the following form,

$$\varepsilon = \sigma \left(\frac{1}{E_0} + \frac{1}{E_1} t^n \right)$$

$J = \frac{\epsilon}{\sigma} - \frac{1}{E}$

defines, what is technically termed, the creep compliance of the material. Since n is less than 0.10, the creep compliance may be used to determine the relaxation modulus, which may be written as follows:

$$\sigma = \varepsilon \left(\frac{1}{E_0} + \frac{1}{E_1} t^n \right)^{-1}$$

This equation may be used to describe stress as a function of time with strain being held constant, which is the technical description of the stress relaxation test.

It is noted from the results that a large amount of creep strain is accumulated on the loading portion of the creep tests performed. This creep component of strain will not be recovered upon a temperature decrease while at constant stress, but will be rapidly expended by the material upon temperature increase at constant stress. This may be simply reiterated as follows:

- GFRP will not exhibit a change in strain due to increasing modulus via a temperature decrease.
- GFRP, on the other hand, will exhibit a change in strain due to a decrease modulus under constant stress via a temperature increase.

In like vein, in situations where total strain is being held constant, the stress on the material will not increase due to a modulus increase resulting from temperature decrease. Correspondingly, the stress on the material under a constant strain condition will decrease if the modulus decreases due to temperature increase.

Creep At Temperatures Other Than Room Temperature

Creep behavior and stress-strain behavior of GFRP at temperatures other than 300°K (room temperature) may be mathematically described by adjusting the general creep equation described earlier. A replacement for t by ξ will permit use of the creep equation at various temperatures down to 4°K. The new generalized equation is written as follows:

$$\varepsilon = \sigma \left(\frac{1}{E_0} + \frac{1}{E_1} \xi^n \right)$$

where ξ is temperature shifted real time and is defined as follows:

$$\xi = te^{Q \left(\frac{1}{T_0} - \frac{1}{T} \right)}$$

where Q is a constant,

t is the real time,

e is the naperian log base or 2.71828.

T_0 is the absolute reference temperature in °K and

T is the absolute test temperature in °K.

Making the substitution for real time by a temperature shifted time, ξ , through an Arrhenius based equation is a mathematical method of employing the time-temperature super-position principle. In simpler terms, the time temperature super-position principle effectively states that as the temperature decreases the real time for a given event increases. Moreover, the time-temperature super-position principle employed in the creep equation effectively states that a given amount of creep will require an identical amount of temperature shifted real time, ξ , regardless of temperature; the real time for this given amount of creep extension, however, will be drastically different depending on the temperature.

Respectfully submitted,

PACKER ENGINEERING ASSOCIATES, INC.

E. M. Caulfield

Edward M. Caulfield, Ph.D.,
Director of Mechanical Engineering

$E_1 = \frac{\sigma}{\epsilon_1}$

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TABLE 1

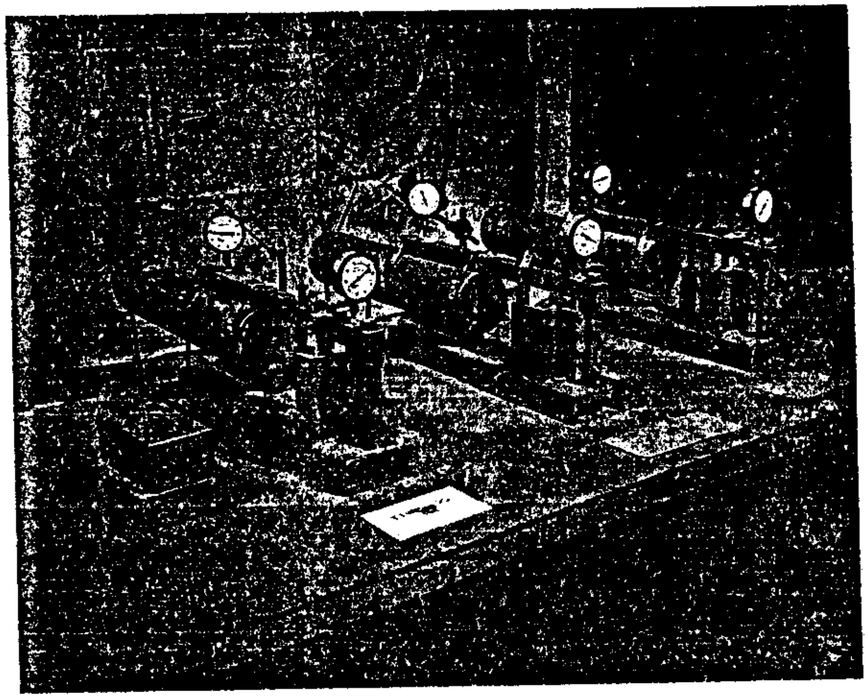
COMPOSITE MATERIAL PROPERTIES

$E_{norm} = \frac{1}{2}(E_0)$

SAMPLE	E_0* (assumed)	E_1 (m=1)	n
G10-2	1.5×10^6	1.31 ~~2.10~~ $\times 10^6$	~~0.063~~ .026
G10-3	1.5×10^6	1.44 ~~2.28~~ $\times 10^6$	~~0.051~~ .032
G10-4	1.5×10^6	1.37 ~~2.10~~ $\times 10^6$	~~0.040~~ .0416
G11-2	1.5×10^6	1.42×10^6	0.032
G11-3	1.5×10^6	1.46×10^6	0.030
Laminate	~~2.0×10^6~~ 1.0×10^6 ?	2.0 ~~1.97~~ $\times 10^6$	~~0.030~~ .026

*Assumed value at 4°K

Neg. No's. 1 & 2



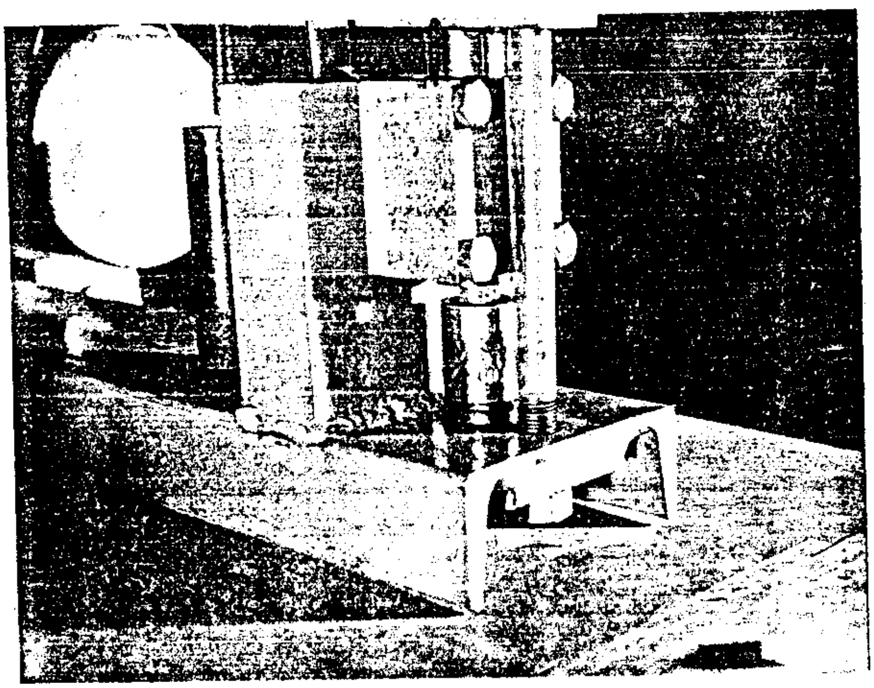
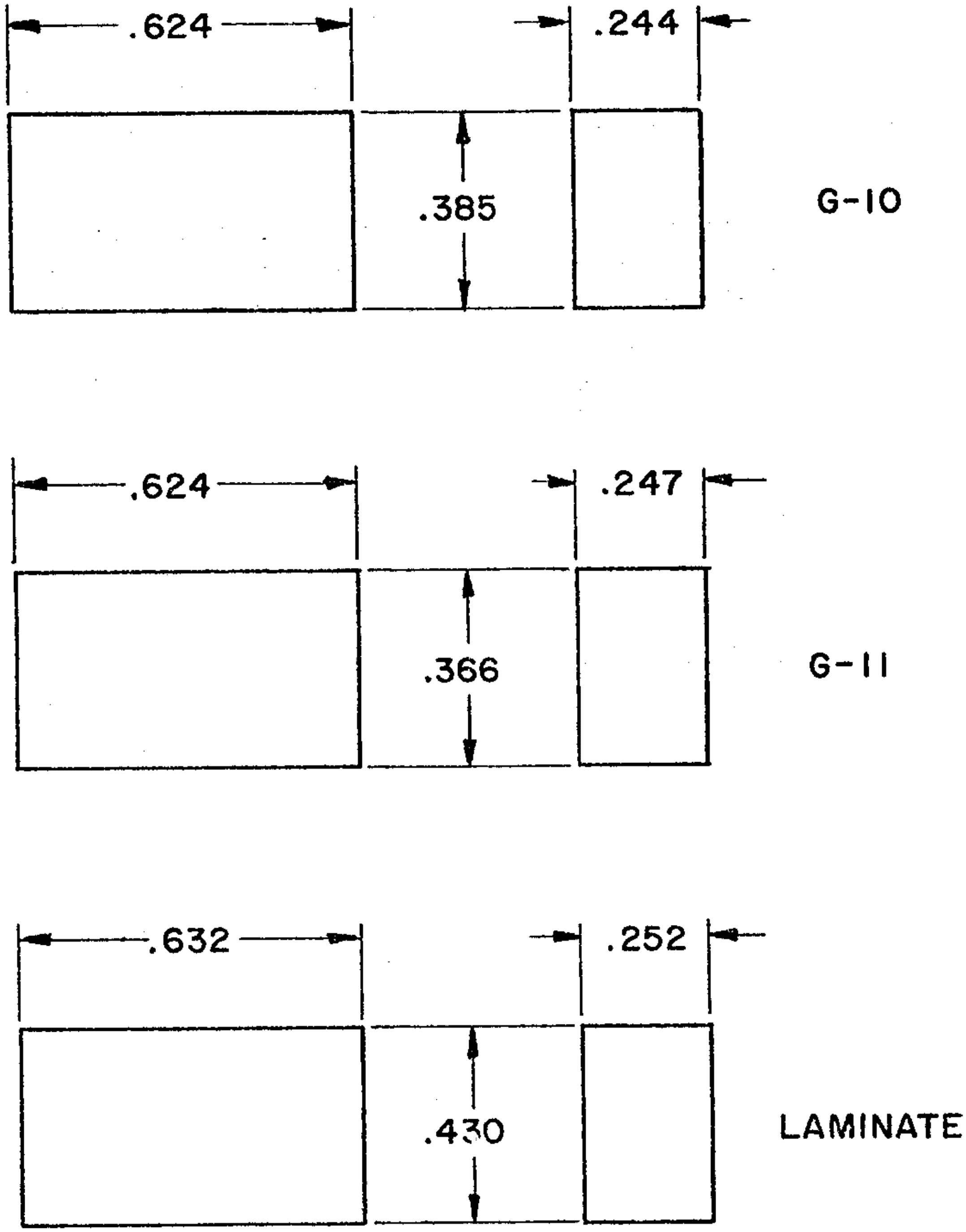
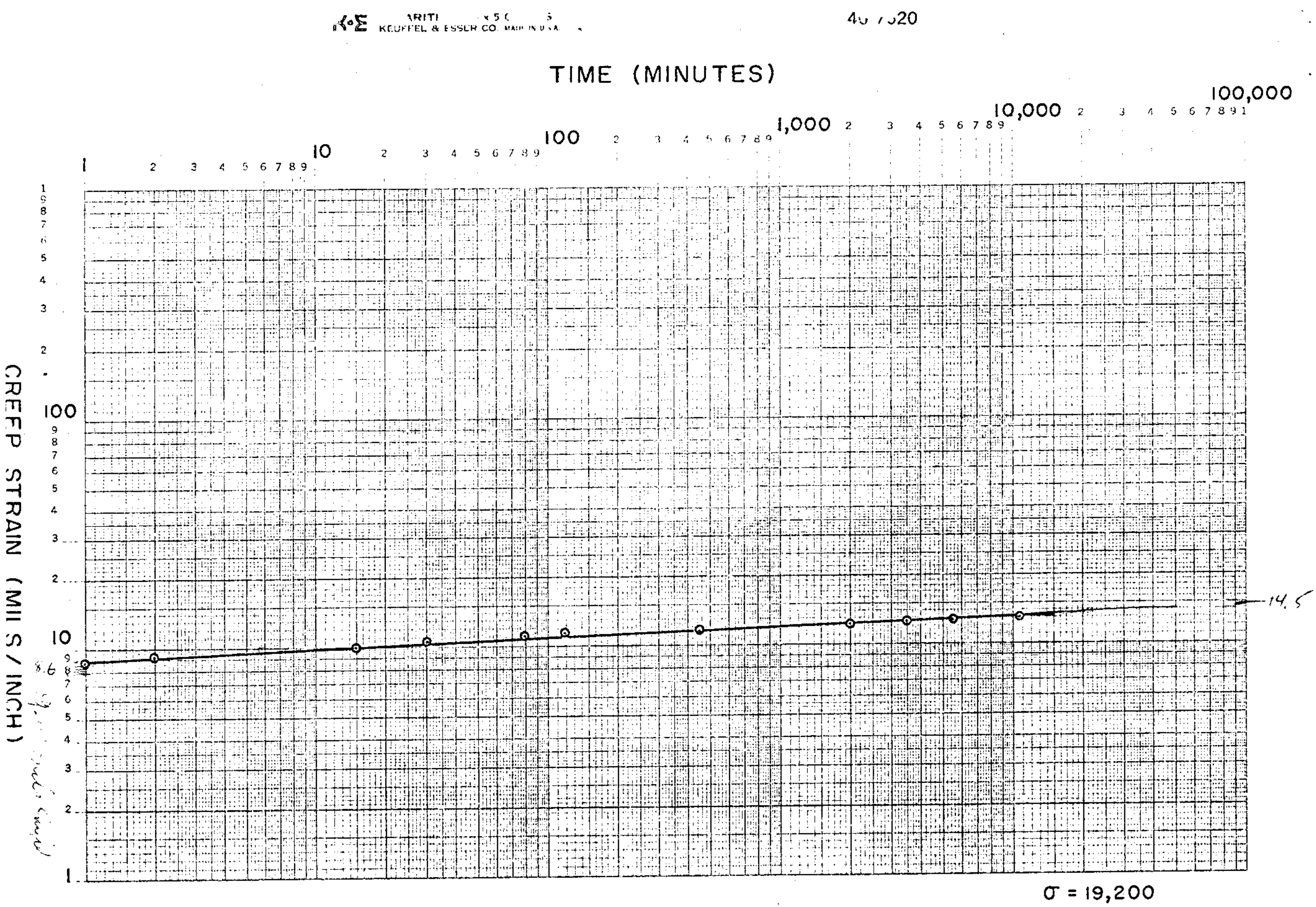


FIGURE NO. 1
TEST APPARATUS



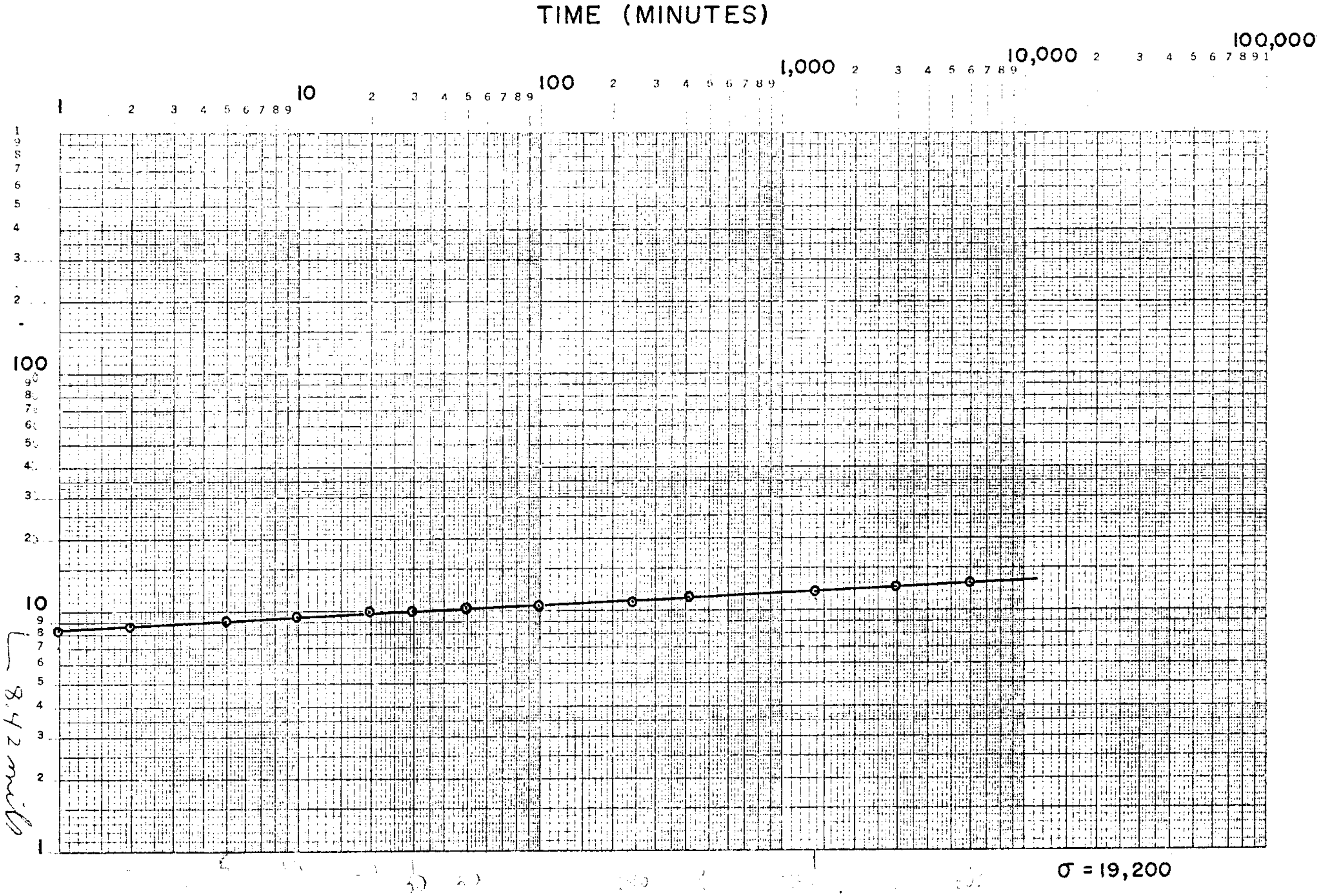
SPECIMEN DIMENSIONS

FIG. 2



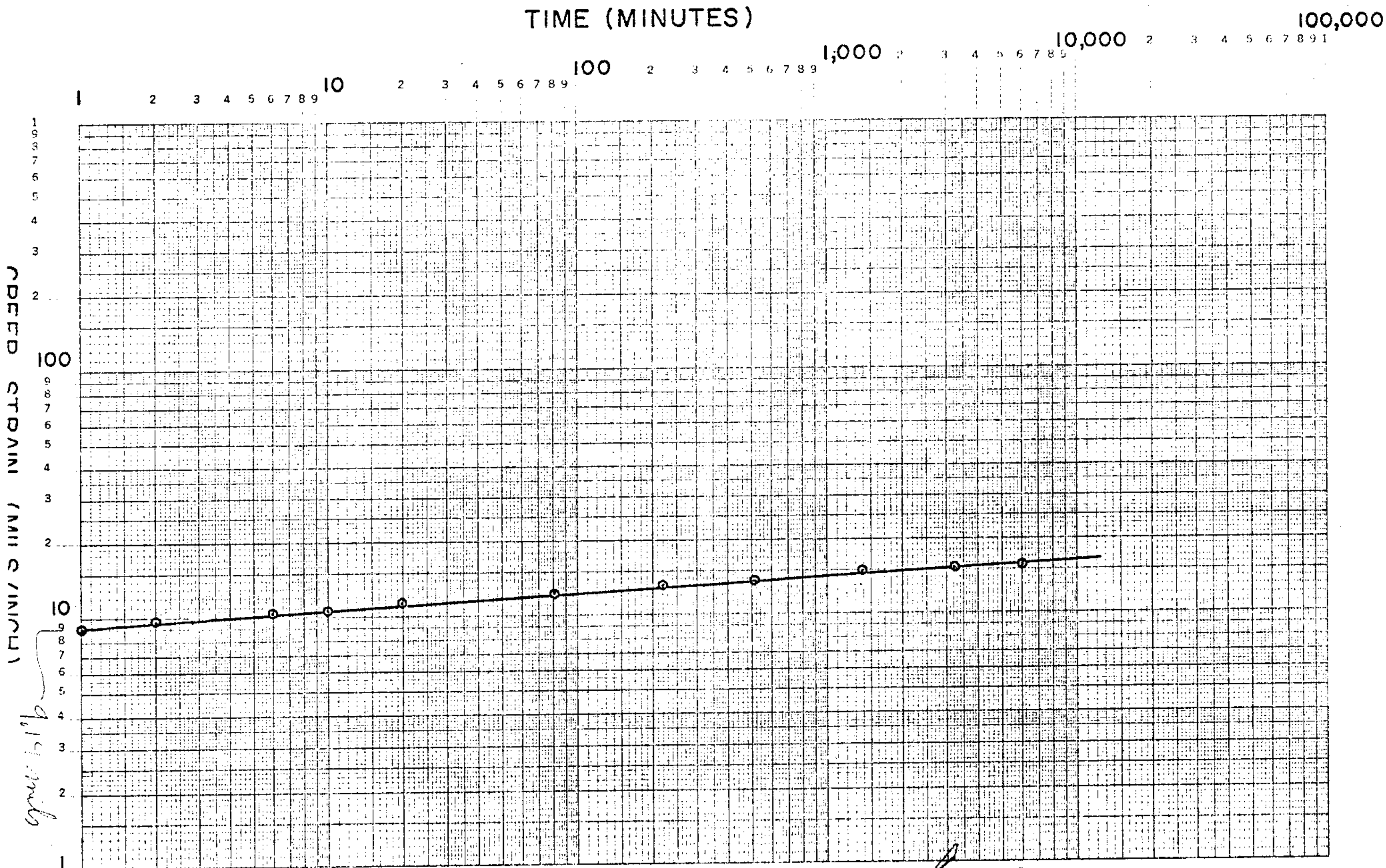
SAMPLE: G 10-2

FIGURE NO. 3



SAMPLE: G-10-3

FIGURE NO. 4



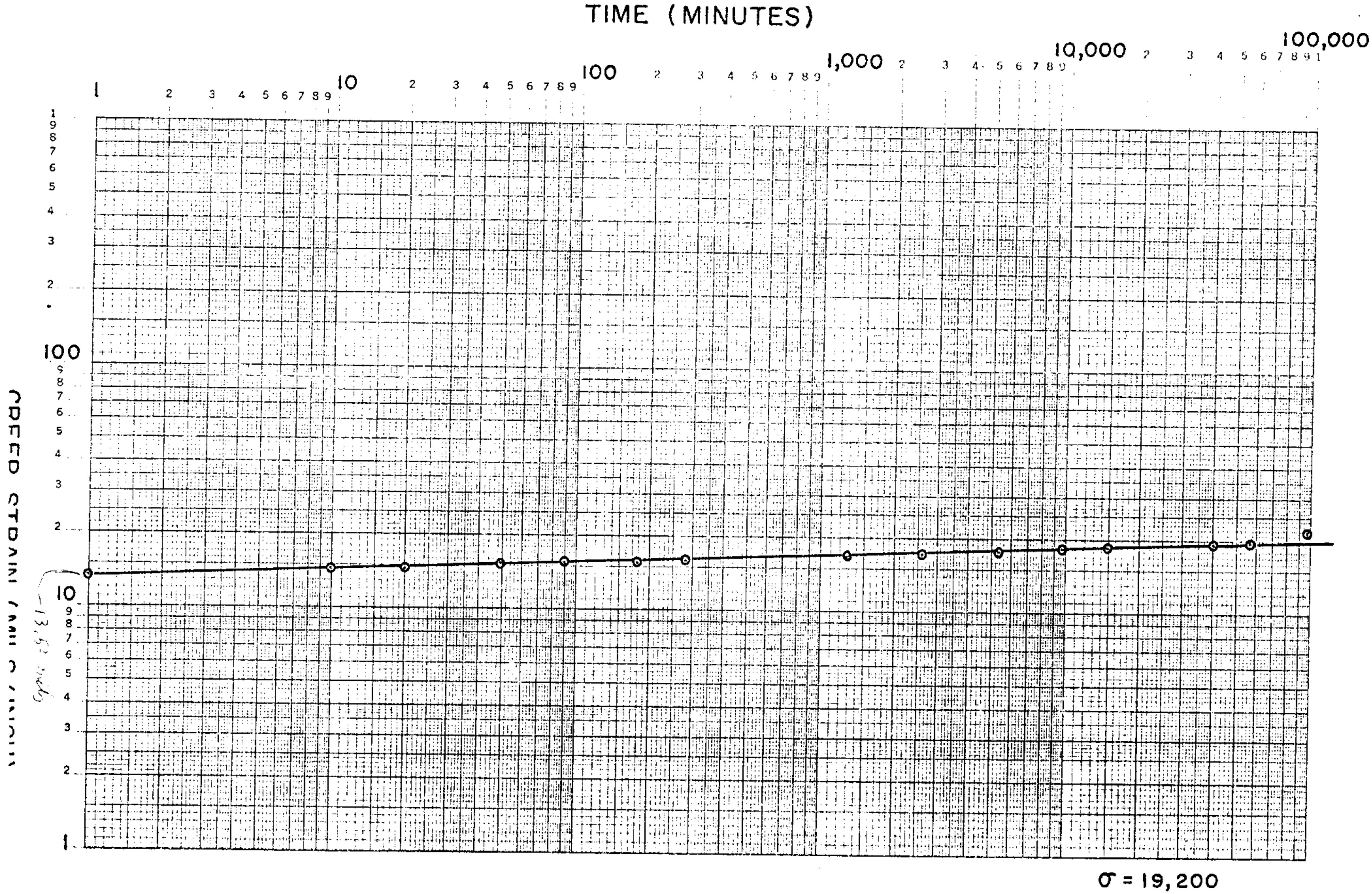
error in slope

$\sigma = 19,200$

SAMPLE: G10-4

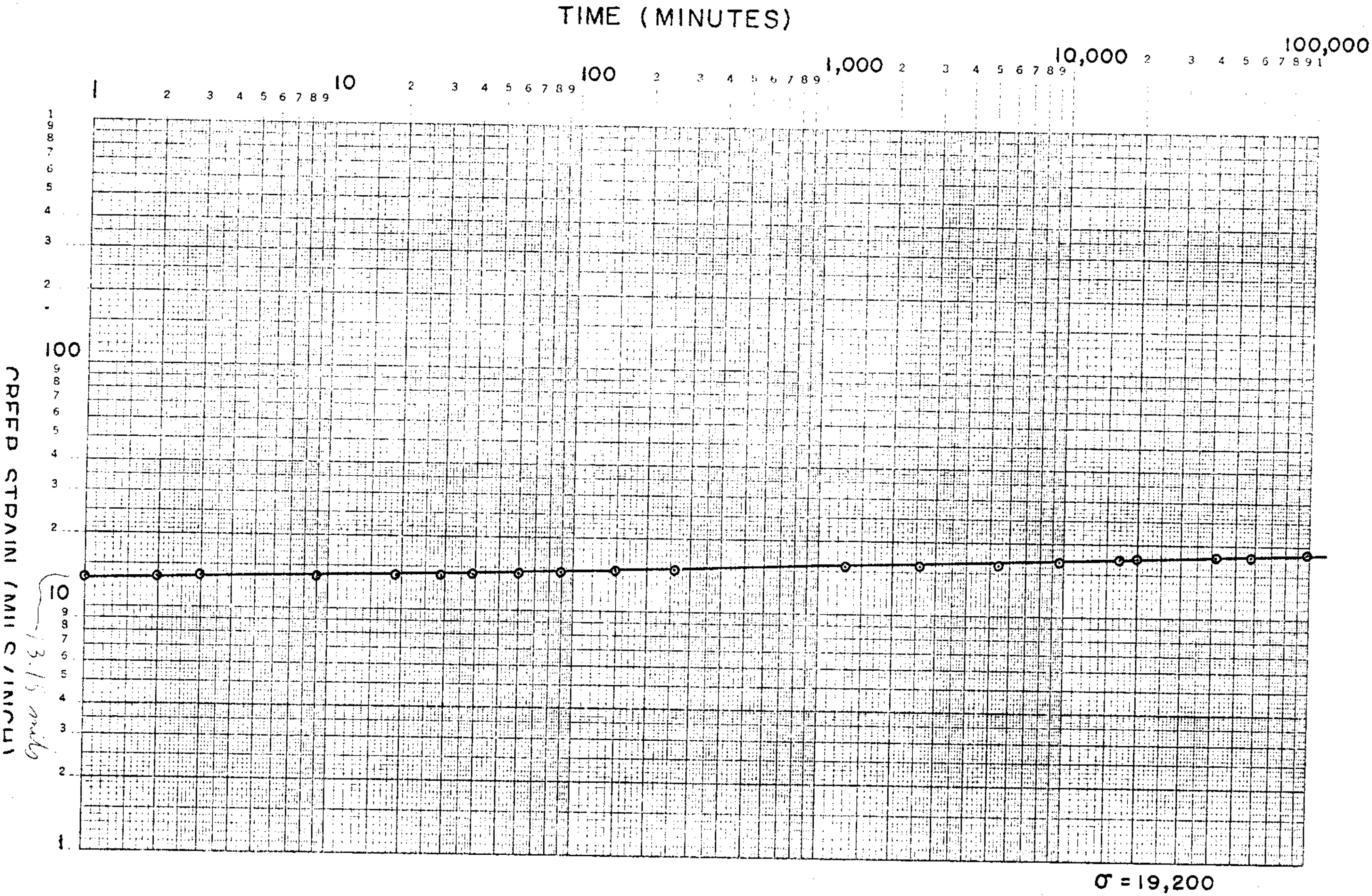
FIGURE NO. 5

K&E LOGARITHMIC 3 x 5 CYCLES KEUFFEL & ESSER CO. MADE IN U.S.A. 46 7520



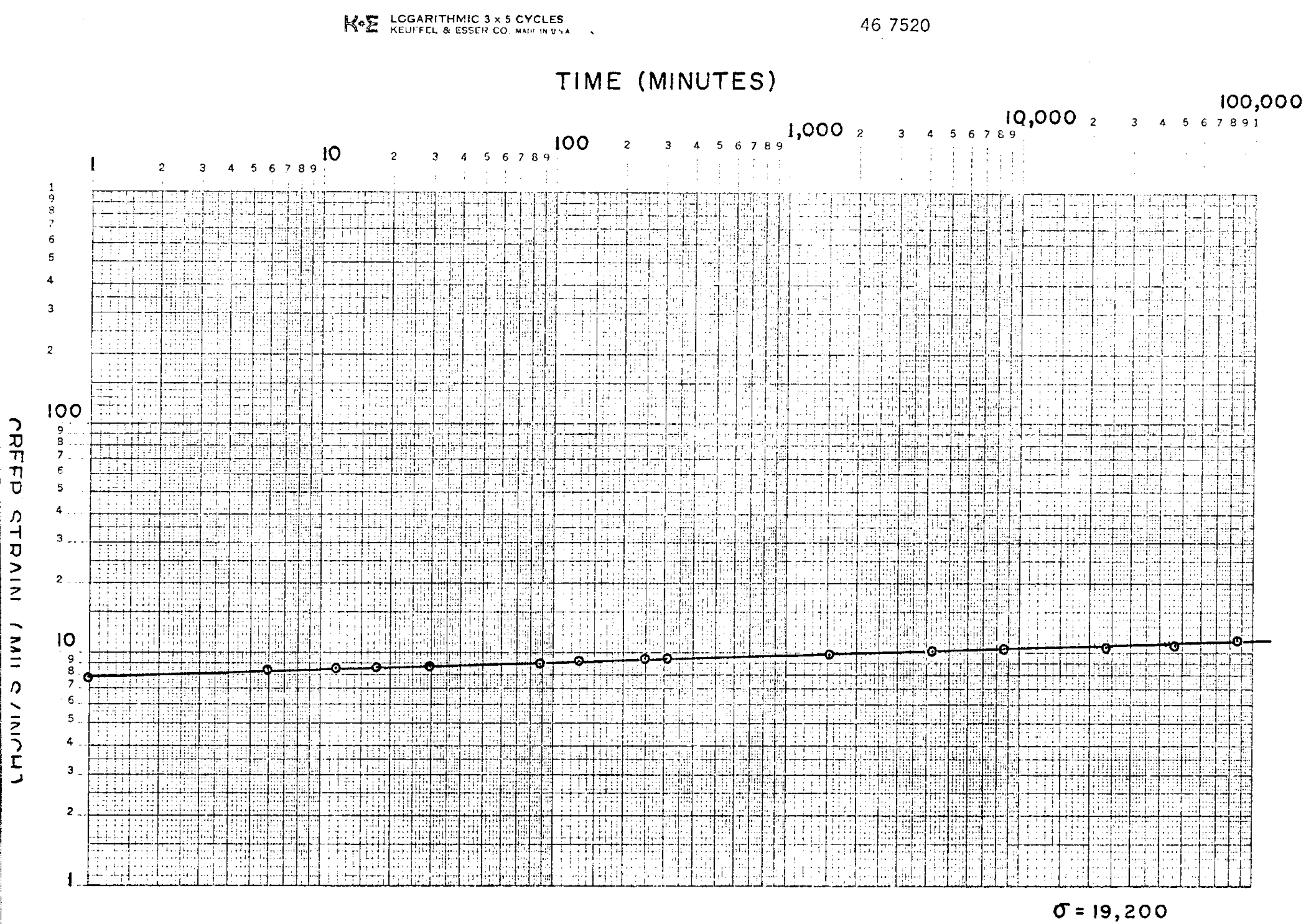
SAMPLE: G-11-2

FIGURE NO. 6



SAMPLE: G-11-3

FIGURE NO. 7



SAMPLE: LAMINATE

FIGURE NO. 8

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Title Fermi G10 Sample # 4 Station # 3

File No. 3-343.201 By EMC

E	D Time (Min)	C-E	C Creep Strain (μ in/in)		
.0090	1	.007597	.001403 + .015	.003530 =	.016403
.0096	2	.007846	.001754	.003512	.016754
	3		.002105		.017105
.0102	6	.007709	.002491		.017491
	7		.002631		.017631
.0105	10	.007606	.002894		.017894
	15		.003157		.018157
.0112	20	.007604	.003596		.018596
	30		.003684		.018684
.0120	80	.007579	.004421		.019421
.0130	226	.007737	.005263	.003337	.020263
	396		.005614		.020614
.0135	516	.007711	.005789		.020789
.0148	1385	.008134	.006666		.021666
	1555		.006701		.021701
	1711		.006789		.021789
	2957		7105		.022105
.0150	3377	.007532	7368		.022368
	5693		7807	.003359	.022807
.0160	5993		7894	.003306	.022894
	7100	.008106	7982	.003201	.022982

AS Read Creep Data.

[illegible]

appears to be on plotter
creep strain + 7597 μin/in in final report
[illegible]

PACKER ENGINEERING Date

Title

File No. 3-443-261 By

STATION #3 Sample #4

START 3/5/80 9:44 A.M.

$$B = \left(\frac{A}{6} + .0036\right) \times 10^{6}$$

time (Min)	B Creep Strain (μ) *
1	4933
2	5266
3	5600
6	5966
7	6100
10	6350
11	6416
13	6516
15	6600
20	7016
30	7100
80	7800
226	8600
396	8933
516	9100
1385	9933
1 1555	9966
2 1711	10050
3 ~~4682~~ 2957	10350
4 ~~5102~~ 3377	10600
5 ~~7438~~ ~~5698~~ 3613	11016
6 ~~7727~~ ~~6287~~ 5993	11100
7 8867 ~~7127~~ 7109	11183

Page ______ of ______

PACKER ENGINEERING Date .4(6 .4(15) = 6

Title

File No. [illegible] By

SAmPle #4

3-8-80 -9:44 AM

A

~1- 0.008 —

2- 0.010

3 - 0.012
6 - 0.0142
7 - 0.0150
10 - 0.0165
11 - 0.0169
13 - 0.0175
15 - 0.018

26 - 0.0205	10:04				80	80
30 - 0.021					120	120
80 - 0.0252	11:04 -				30	26
					32	226
226 - 0.030	13:30					
396 0.032	16:20		(396)			
516 0.033	18:18		(516)	14 ||||||||||||||| + 29		
1385 .038	8:47	3/7	(1385)			
15 (1) .0382	11:38		1555			
(2) .0387	14:14	3/7	(1711)			
(3) .0405	11:00	3/8	21 ~~4682~~ 295			
(4) .042	13:00	3/8	7	5102		
(5) .0445	8:36	3/10	840+36 = 876			
(6) .045	1:43	3/10				
(7) .0455	8:30	3/11	17	1140		

60 / 60

0

Page of

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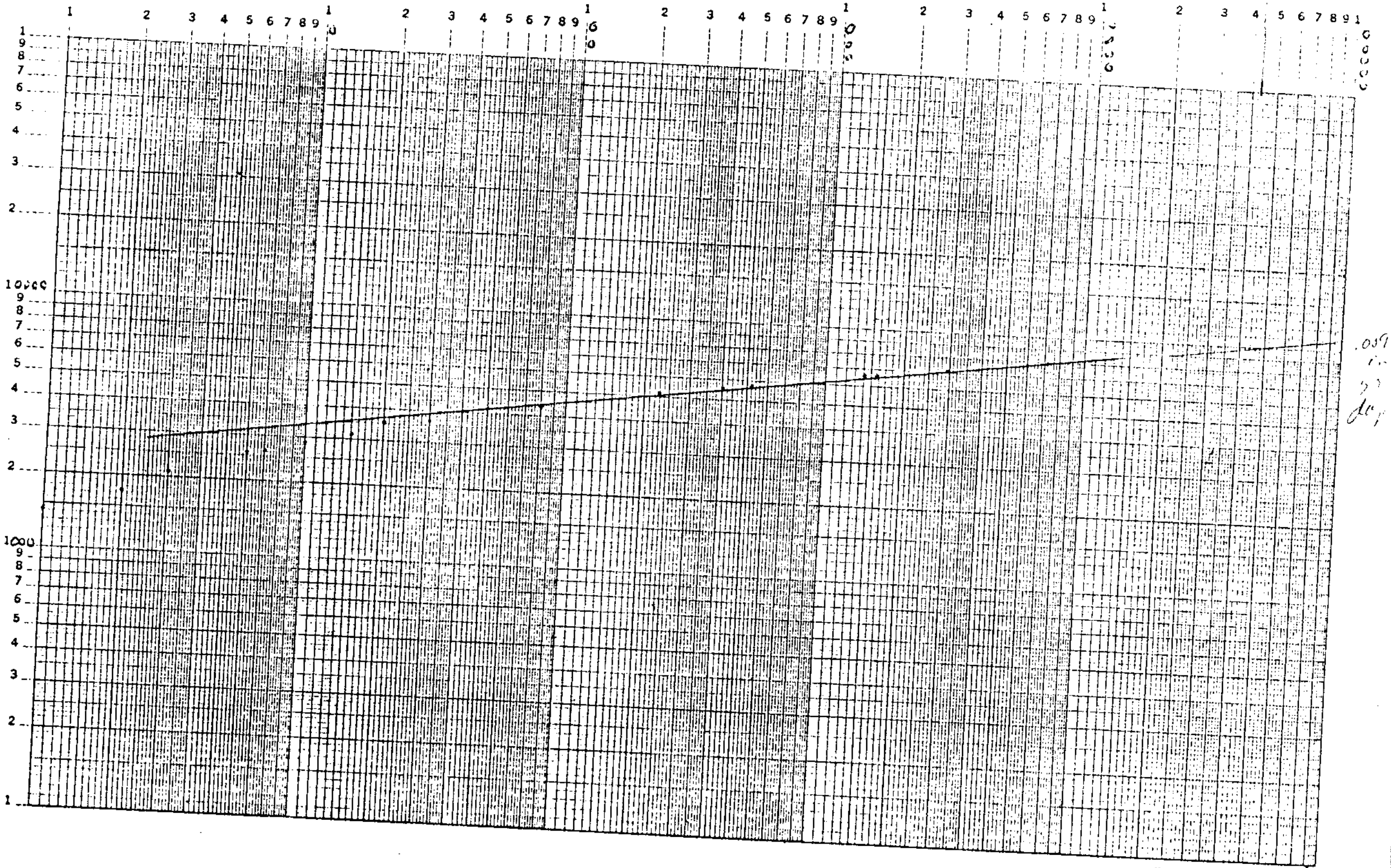

G-10 SP#4
CT#2

$\epsilon_{TOTAL} = \epsilon_1 (t-t_1)^n + \epsilon_0 -$

$.013501 = .000701 +$

PACKER ENGINEERING Date 4/8/80

Title Fermi - G11 Sample #2 Station #2

File No. 3-343.201 By EMC.

$701 + \frac{\sigma}{2E} - \frac{\sigma}{E_0}$

	Time (Min)	ϵ: Strain (M in/in)	$\epsilon_1(t-t_1)^n$ As Read Strain
1	1	.013501	701
2	10	.014203	1403
3	20	.014554	1754
4	30	.014729	1929
5	40	.015080	2280
6	50	.015168	2368
7	60	.015256	2456
8	70	.015291	2491
	85		
1	90	.015431	2631
	120	.015571	2771
	180	.015764	2964
	288	.015975	3175
3	1296	.016747	3947
4	1608	.016835	4035
5	2604	.017098	4298
	5436	.017536	4736
7	5940	.017536	4736
	9720	.018063	5263
9	12720	.018238	5483
0	15540	.018361	5561
1	17340	.018414	5614
22	19860	.018501	5701

-12800 =

.028
.000701
.013501

$\frac{\sigma}{1.28 \times 10^6} = .0128 = \frac{\sigma}{E_0}$

12800
.031301

As Read Creep Data

Strain - (.012800) = creep

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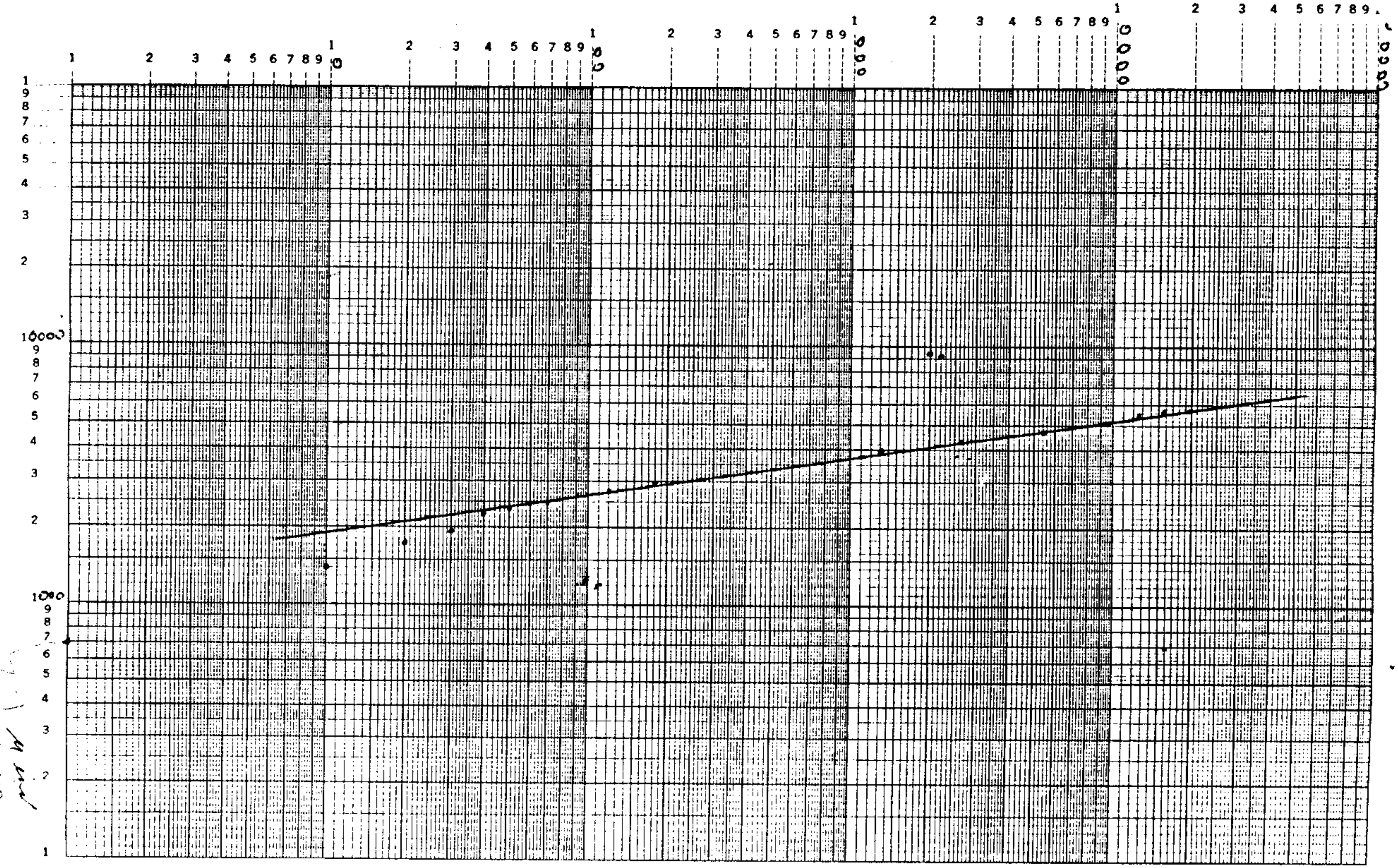

G-11
Sample #2
Station #2

K·E LOGARITHMIC 3 x 5 CYCLES
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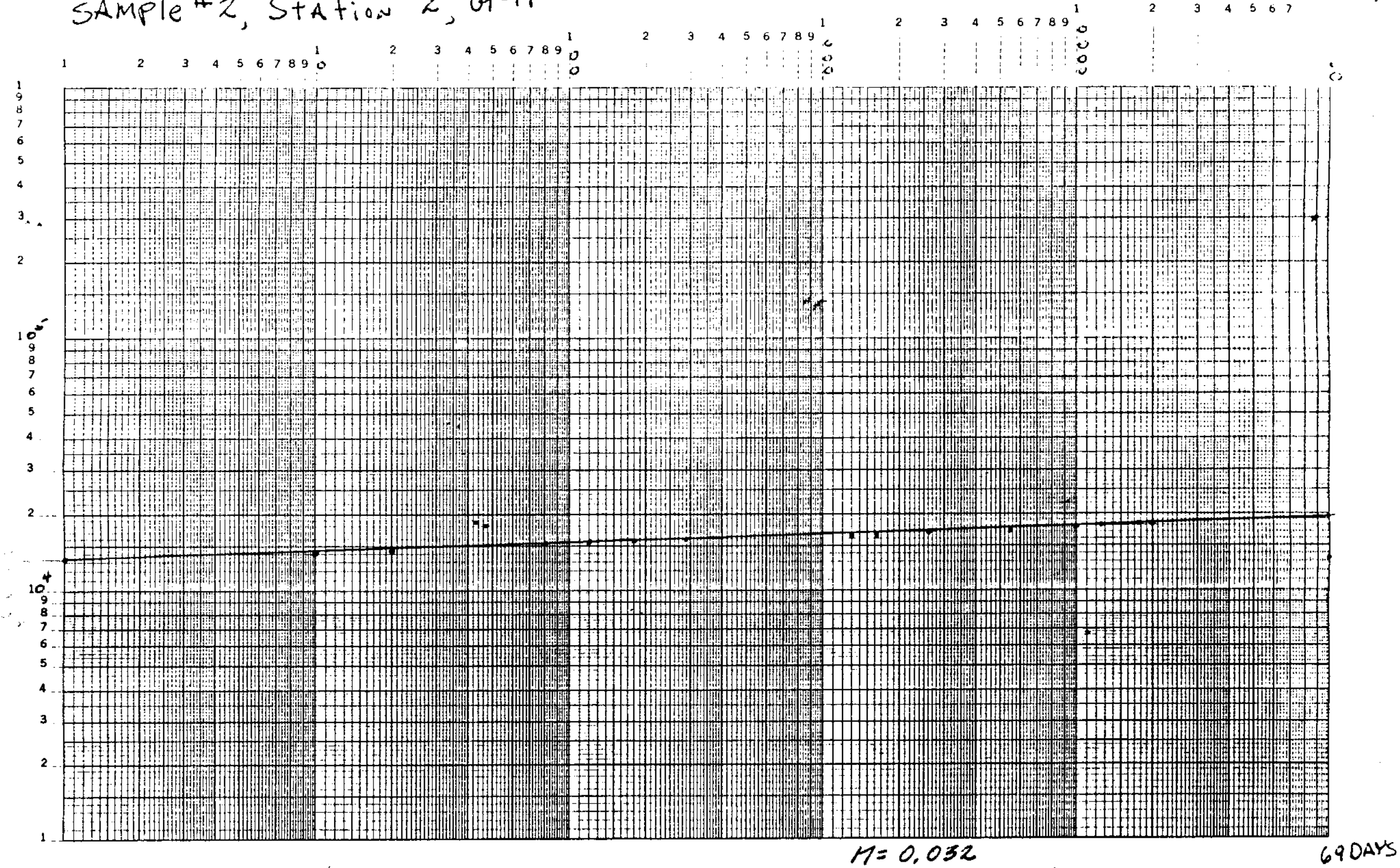
SAMPLE #2, Station #2, G-11



$M = 0.032$

$E_1 = 1.42 \times 10^6$

ln t	ln(ε - .01)	ln(ε - .007)
0	-5.6547066	-5.0357793
2.302	-5.4719567	-4.9332577
~~2.99~~ 2.4957323	-5.3917493 ~~-4.[illegible]~~	-4.8856781
3.4011974	-5.3540415	~~-4.9618451~~ -4.8627758
3.6888795	-5.282444	~~-4.9618451~~ -4.8183634
3.912023	-5.2652695	-4.8075312
4.0943446	-5.248385	-4.7968151
4.2484952	-5.241748	-4.7925847
4.4998097	-5.215632	-4.7758397
4.7874917	-5.190807	-4.7593709
5.1929569	-5.1561236	-4.7371029
5.6629605	-5.1201712	-4.7133123
7.1670379	-4.9986573	-4.6307957
7.3827465	~~-.006835~~ -4.9856988	-4.6218078
7.864804	-4.9479422	-4.5954179
8.6007988	-4.8880637	-4.5529573
8.6894644	-4.8880637	-4.5529573
9.1819409	-4.8204696	-4.5041491
9.4509308	-4.7989977	-4.4884544
9.6511726	-4.7841772	-4.4775688
9.7607713	-4.7778583	-4.4729146
9.8964629	-4.767578	-4.4653213

6-11
Sample #2
Station 2

PACKER ENGINEERING Date 4/8/80

Title Fermi - G-11 Sample #3 STATION #3

File No. 3-543.201 By EMC

Time (Min)	Strain (M in/in)	As Read Creep
1	.012975 ~ 12801	175
2	.013150	350
3	.013326	526
9	.013589	789
19	.013852	1052
29	.013992	1192
39	.014098	1298
60	.014291	1491
90	.014484	1684
150	.014694	1894
258	.014905	2105
1266	.015607	2807
2574	.015870	3070
5406	.016308	3508
5910	.016400	3600
9690	.016835	4035
11940	.016922	4122
15510	.017063	4263
17310	17185	4385
19830	17221	004421

0128

.017221

As Read Creep

N = 20

Strain − (.012808) = creep

$\left(\frac{\sigma}{E_0}\right)$

$\sigma = 0$

$\epsilon = .001$

$\epsilon - \epsilon_0$

$\sigma = ~~22,000~~ \; 19,200$

$\epsilon = \frac{19200}{1.5 \times 10^6}$

$E_0 = 1.553398 \times 10^6$

$\epsilon = .0128$

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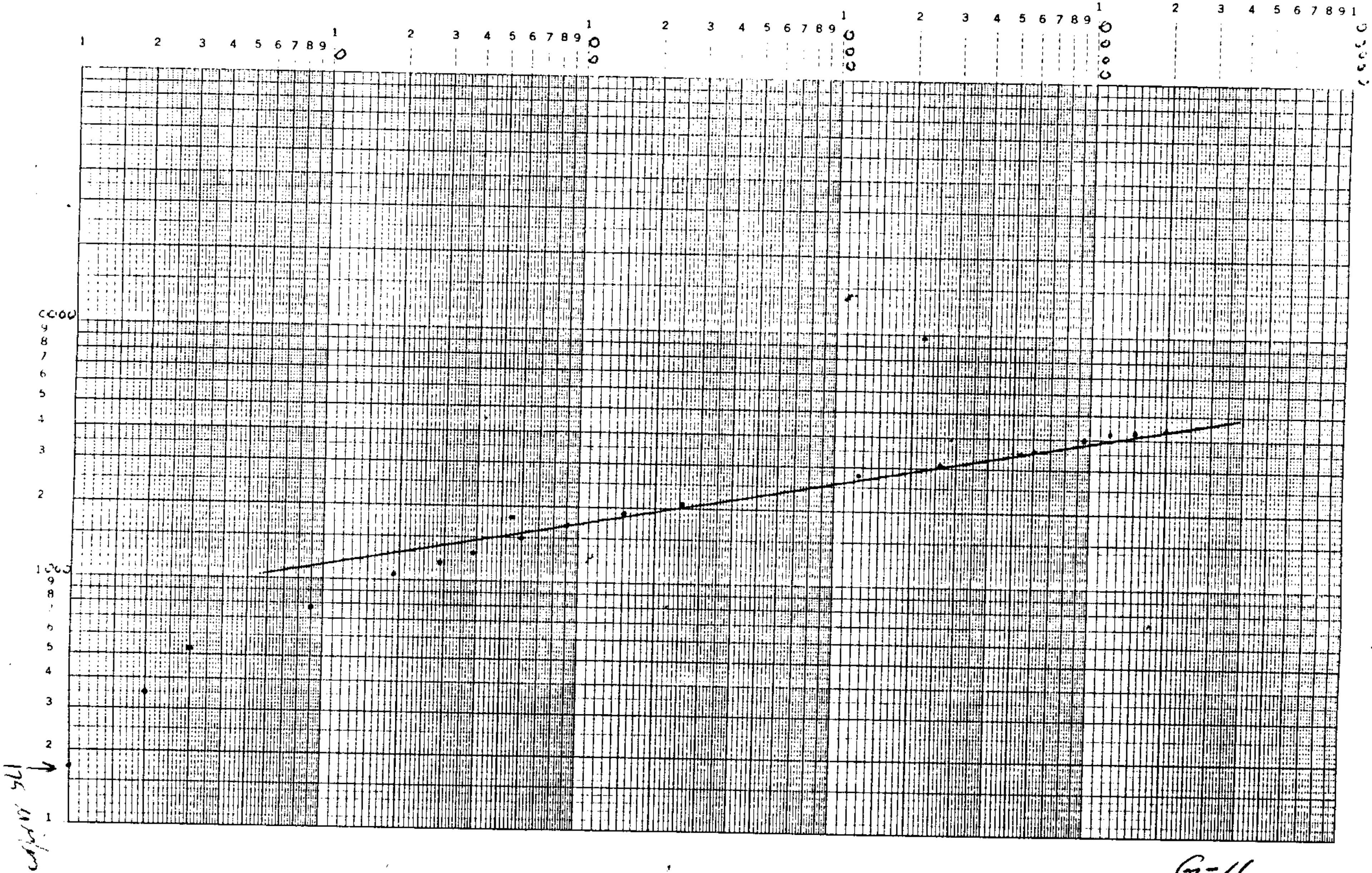

AS Read Creep

G-11
Sample #3
Station #3

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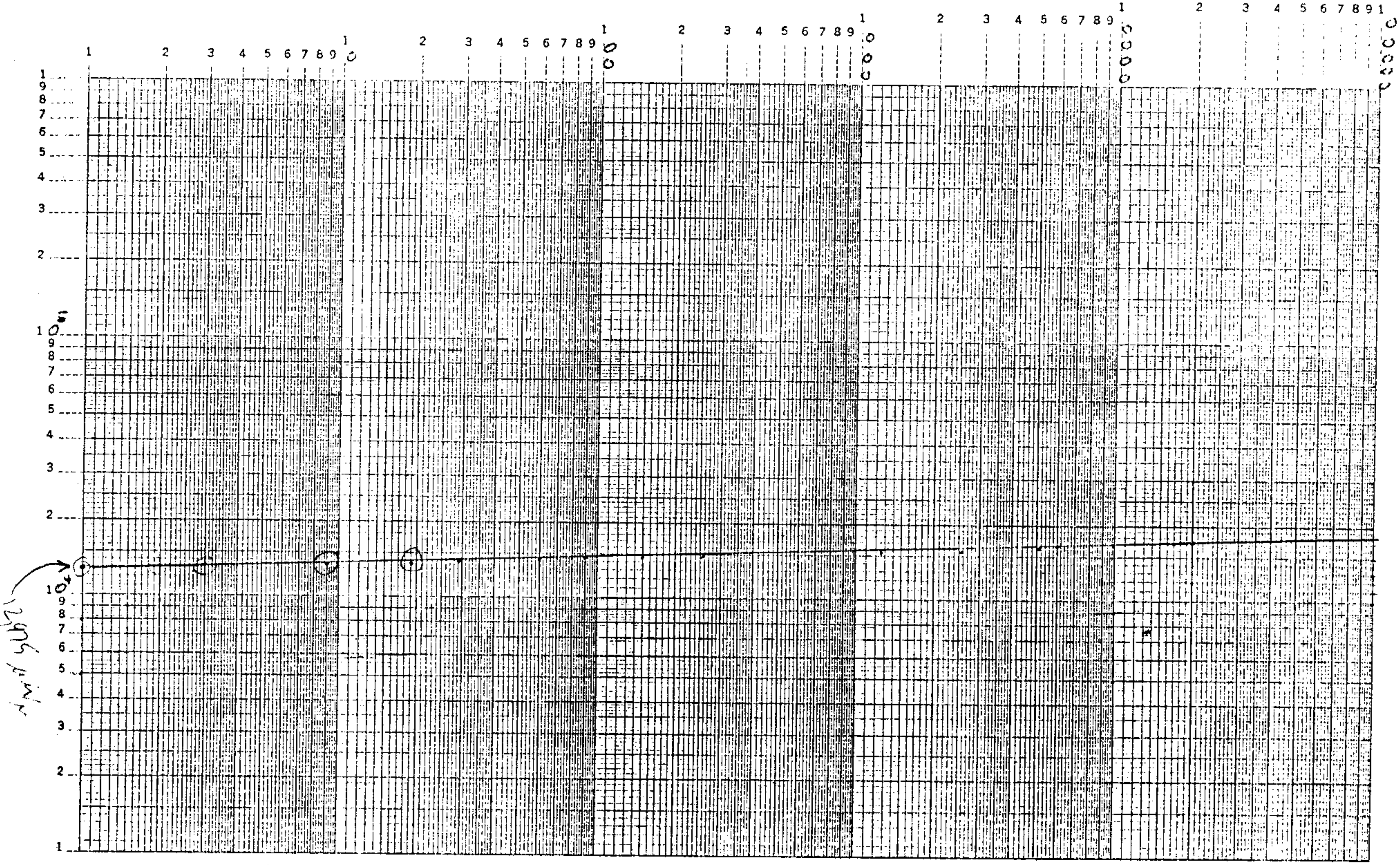


$C_1 = ,$ [illegible]

$F_1 \quad \frac{\sigma}{\epsilon}$

$$E_1 = \frac{19200}{.012975} = 1.4798 \times 10^6$$

$n = 0.030$

$E_1 = 1.476 \times 10^6$ psi

$$n = \frac{\ln(.018) - \ln(.012975)}{\ln 100{,}00 - \ln 1}$$

$$n = \frac{.327}{11.51}$$

$n = .028$

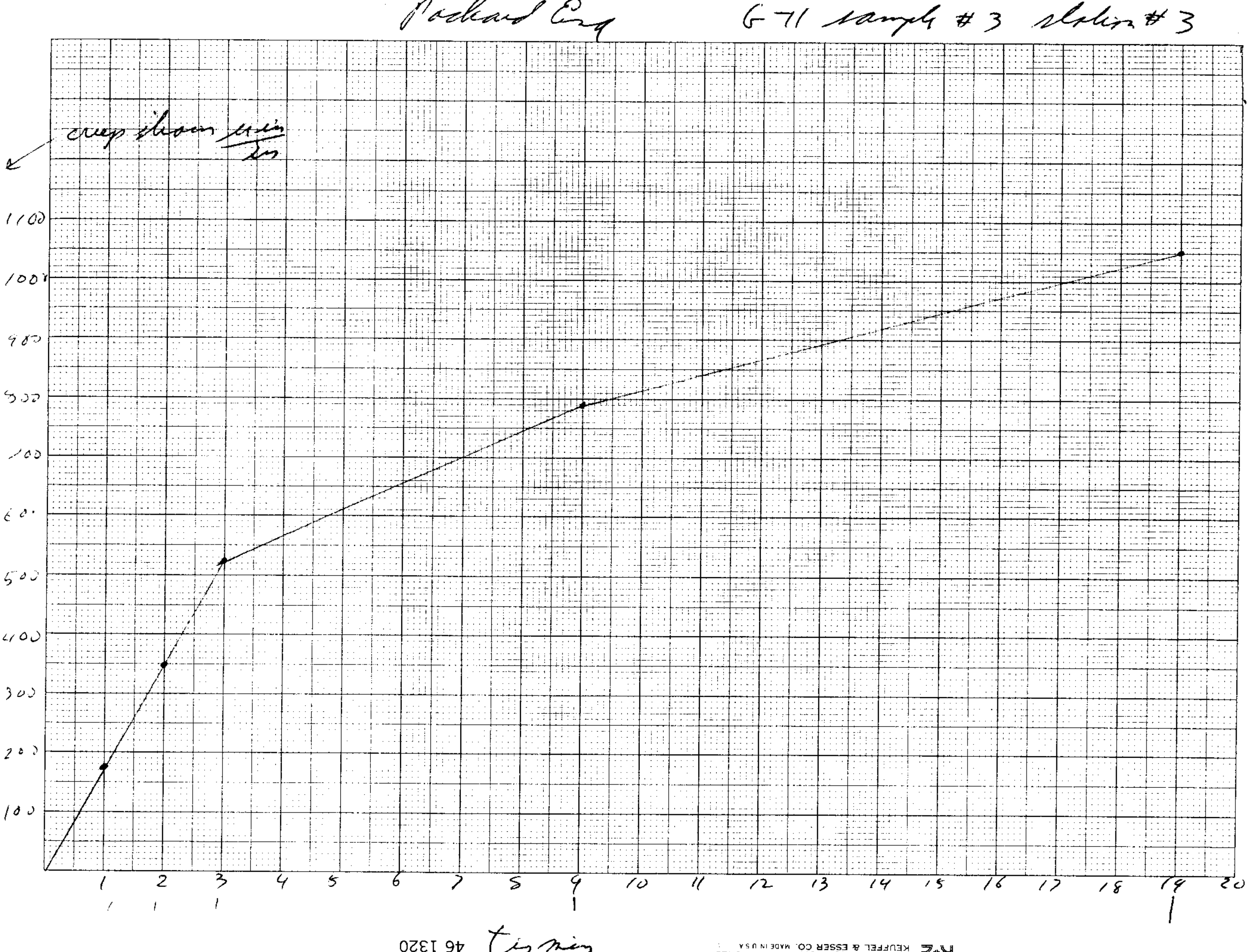
G-11

Packard Eng Data sample 3 station 3

C	E	ln (E -.01	ln (t)
1	.012975	-5.81175112	0
2	.013150	-5.7603528	.69314718
3	.013326	-5.7059849	1.0986123
9	.013589	-5.6298817	2.1972246
19	.013852	-5.5591628	2.944439
29	.013992	-5.5234629	3.3672958
39	.014098	-5.4972562	3.6635616
60	.014291	-5.4512355	4.0943446
90	.014484	-5.4072398	4.4998097
150	.014694	-5.3614702	5.0106353
258	.014905	-5.3175002	5.5529596
1266	.015607	-5.1837395	7.1436176
2574	.015870	-5.1379006	7.8532164
5406	.016308	-5.0659366	8.6077649
5910	.016400	-5.0514573	8.6844011
9690	.016835	-4.9856988	9.1788497
11940	.016922	-4.9730505	9.3876494
15510	.017063	-4.9567155	9.6492403
17310	.017185	-4.9357598	9.7590396
19830	.017221	-4.9307618	9.8949512

plot ln(E-.01) vs ln T

5.30


Packard Eng
G 71 sample #3 station #3
creep strain $\frac{\text{u in}}{\text{in}}$
1100
1000
900
800
700
600
500
400
300
200
100
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time hrs

$C = \frac{H}{307}$

PACKER ENGINEERING Date 4/8/80

Title Fermi G10 STATION #2 Sample #3

File No. 3-343.201 By EMC.

F	D Time (Min)	C–E	C Creep Strain μin/in
.0083	1	.001599	~~1174~~ 701 ~ .0004
.0087	2	.007683	1017
	3		1192
	4		1263
.009	5	.007597	1403
	8		1596
.0094	10	.007634	1736
	15		1929
.0099	20	.007813	2087
	25		2192
.0100	30	.007720	2280
	40		2368
	50		2456
	100		2789
	246		3245
	419		3684
	535		3771
	1404		4298
	1575		4385
	1730		4421
	2977		4701
	3397		4824
	5707		5087
	6022		.005263
	7117		.005263
25 ptk	7200	=	5 days

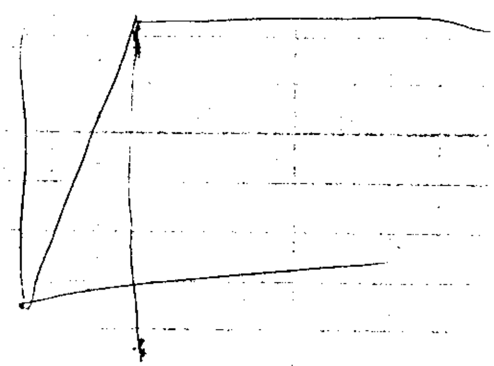
As Read Creep DATA

true $\epsilon - \frac{19,200}{1 \times 10^6} =$

$\frac{\sigma}{E_0}$

$701 + \frac{\sigma}{2E_0} - \frac{\sigma}{E_0}$

701



[illegible] .007 in 30 [illegible]

appears to be plotted creep than [illegible] μin/in in first [illegible]

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STATION #2

PACKER ENGINEERING Date

Title

File No. 3-343.001 By

STATION # 2 Sample # 3

3-5-80 9:23 AM

$\frac{.004}{6} + .0036 = .004267$

lever arm of dial gauge

		A	B		
~1	-	0.004	(4266)		
2	-	0.0058	(4566)		
3	-	0.0068	(4733)		
4	-	0.0072	(4800)		
5	-	0.008	(4933)		
8	-	0.0091	(5116)		
10	-	0.0099	(5250)		
15	-	0.011	(5433)		
20	-	0.0119	(5583)		
25	-	0.0125	(5683)		
30	-	0.0130	(5766)		
40	-	0.0135	- 10:03 (5850)		
50	-	0.0140	(5933)		
100	-	0.0159	- 11:03 (6250)		
246	-	0.0185	13:29 (6683)		
- 419	-	0.021	16:22 (7100)		
- 535	-	0.0215	18:18 (7183)		
1404		0.0245	(7083)	8:47 3-7	
1575	-	0.0250	(7166)	11:38	
1730	-	0.0252	(7800)	~~14:13~~ 14:13	
2977		0.0268	(8066)	11:00 3/8	
3397		0.0275	(8133)	18:00 3/8	
5707		.029	(8433)	8:30 3/10	24+
6022		.030	(8600)	1:45p 3/10	
7117		.030	(	8:30 3/11	12

5250
4266
984

$\frac{.013}{6} + .0036 = .005767$

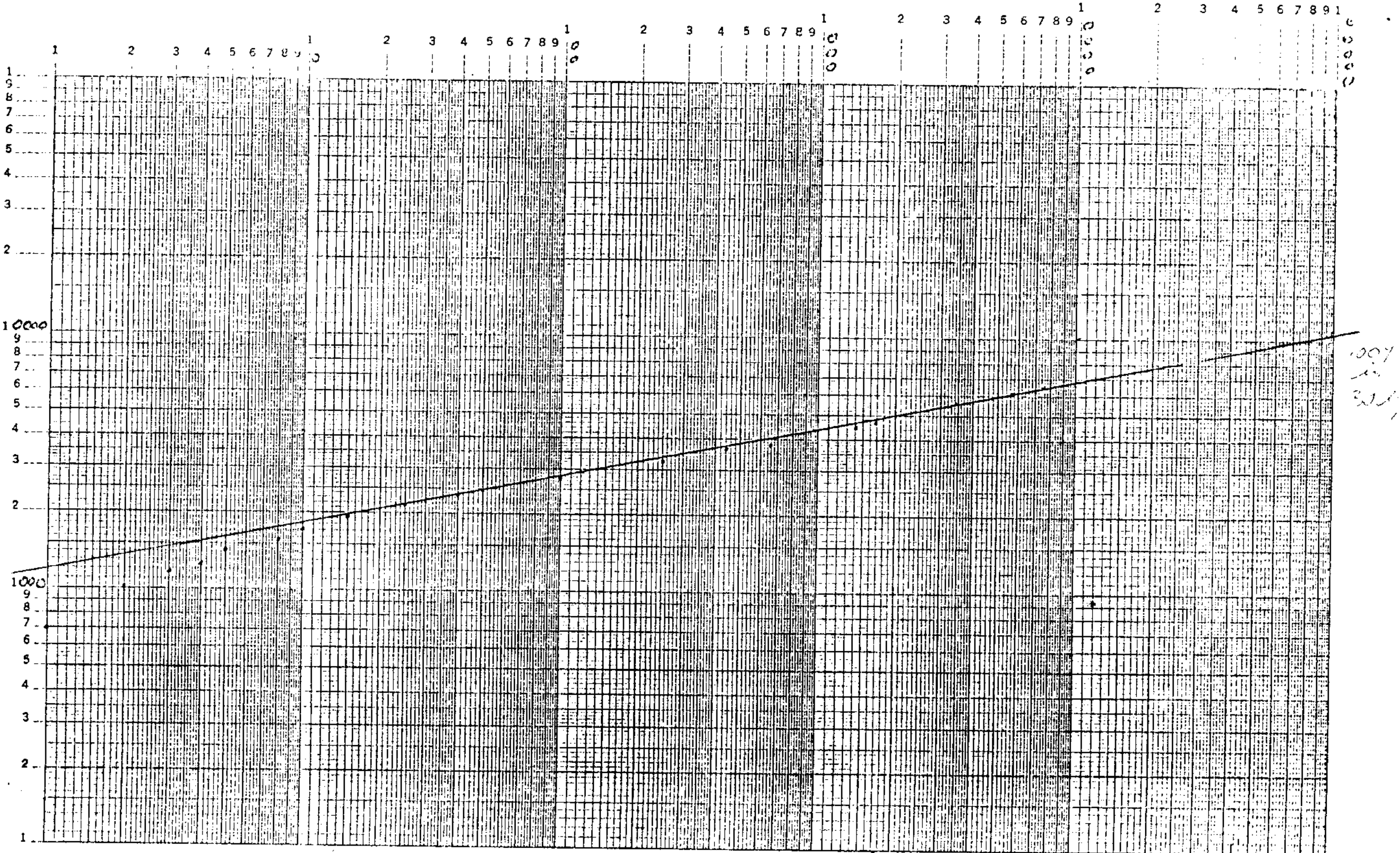
100
120
26
246

$$B = \left(\frac{A}{6} + .0036\right) \times 10^6$$

11000
10000
11000
11 1200
4500 =
5000 C
11000
12000

K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.

46 7520



m = .185
S = 1200 ksi-6
16.7 X 10^6

G10 - S#3
ST #2

creep strain = $\frac{A}{5.7} = \epsilon$

see A on next page

probably A = dial gauge reading

PACKER ENGINEERING Date

Title Fermi G10 Sample #2 STATION #1

File No. 3-343.201 By EMC

(E)	(D) Time (Min)	(C-E)	(C) Creep Strain (μin/in)		
.0087	1	.007560	.001140 + .015	.016140	G=0
.0092	2	.007797	.001403	.016403	Q=.001
	11		.002280	.017280	
.0100 (15)	16	.007544	.002456	.017456	G=...
.0105	30	.007693	.002807	.017807	Q=.0001
	40		.002894	.017894	
	50		.002982	.017982	
.0110	81	.007667	.003333	.018333	22 ...
.0115	120	.007992	.00~~3289~~ 3508	.018508	
.0115	462	.007641	.003859	.018859	G=.010
	660		.004035	.019035	Q=.001
.0122	1288	.007990	.004210	.01921	
	2025		.004508	.019508	
	2764		.004649	.019649	
	3306		.004701	.019701	
.0125	3452	.007764	.004736	.019736	
	3779		.004754	.019754	5.70046
	5025		.004877	.019877	5.70022
.0128	5500 5445	.007853	.004947	.019947	5.70041
	7755		5087	.020087	5.70086
	9185		.005192	.020192	5.7010
.0130	10620	.007737	.005263	.020263	5.7001

data plotted in final report

ave difference is .007748

∴ final data plotted is creep strain + .007748

As Read Creep

compare these with the data on the graphs

corresponds to $\frac{\sigma}{E_0}$ = [illegible] x10⁶

appears to have plotted creep strain + [illegible] μin/in in final report

7544

Page ______ of ______

PACKER ENGINEERING Date

Title

File No. [illegible] By

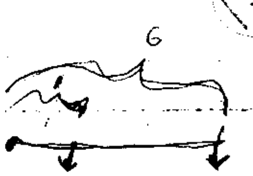
Station # 1 Sample # 2

t	A	B
1	0.0065	4683
2	0.008	4933
11	0.013	5766
16	0.014	5933
30	0.016	6266
40	0.0165	6350
50	0.017	6433
81	0.019	6766
120	0.020	6933
462	0.022	7266
660	0.023	7433
1288	0.024	7600
2025	0.0257	7883
2764	0.0265	8016
3306	0.0268	8066
~ 3452	0.027	8100
✓ 3779	0.0271	8116
✓ 5025	0.0278	8233
✓ 5445	0.0282	8300
— 7755	0.029	8433
35 ~~[illegible]~~ ~~8070~~	.0296	8533
10820 ~~9570~~	.030	8600

$$B = \left(\frac{A}{6} + .0036\right) \times 10^6$$

$$E_{m} = \frac{\sigma}{\epsilon} = \frac{\sigma}{\epsilon} \frac{1.9200}{.0036\,(.385)} \quad 2.053 \times 10^6$$

$10^{?}$ .0036 = deformation during loading?



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K+E LOGARITHMIC 3 x 5 CYCLES
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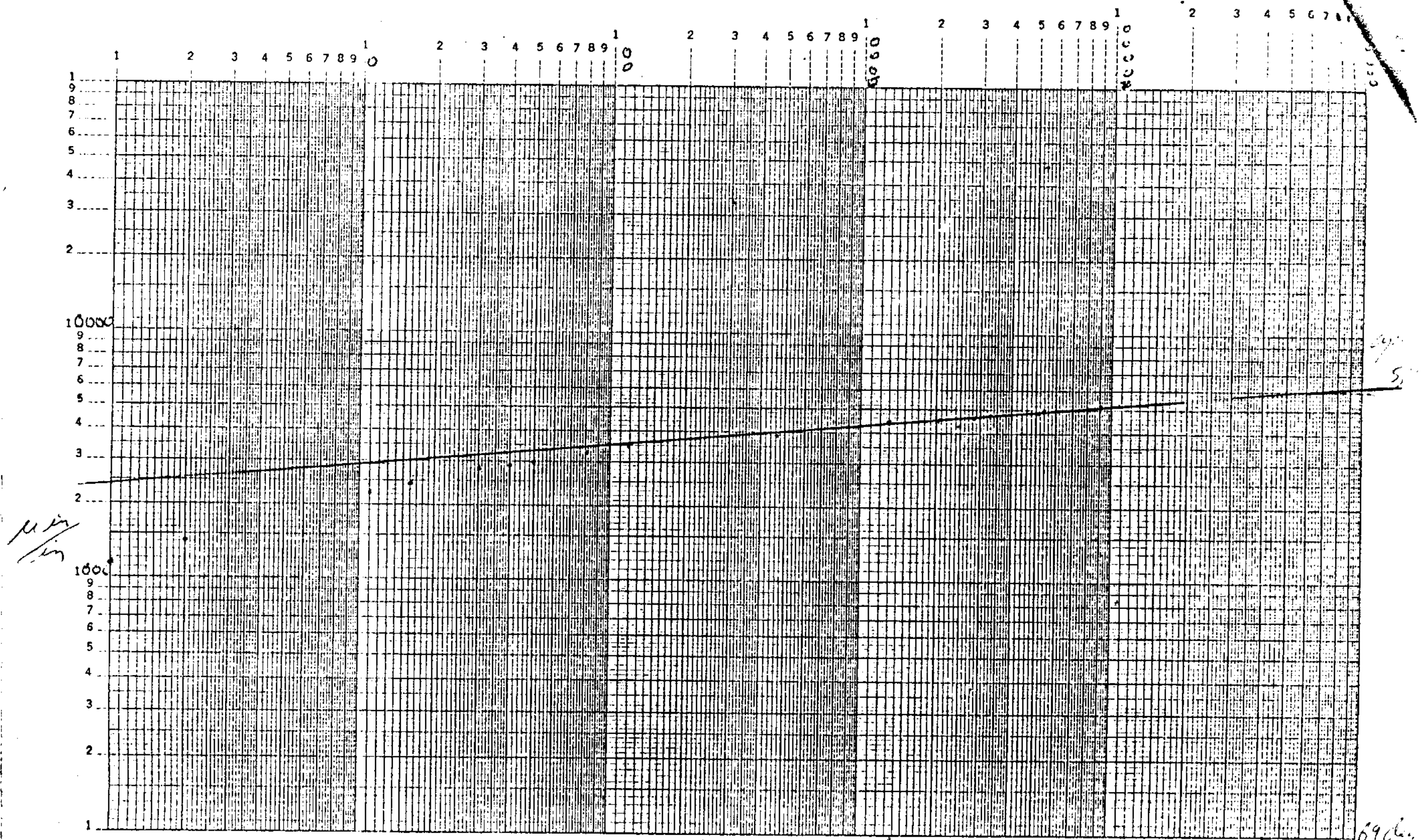
46 7520



10 min

1.17 hrs

$m = .082$

$= 2400 \times 10^{-6}$

$= 8.33 \times 10^{5}$

.69 days
16 hrs

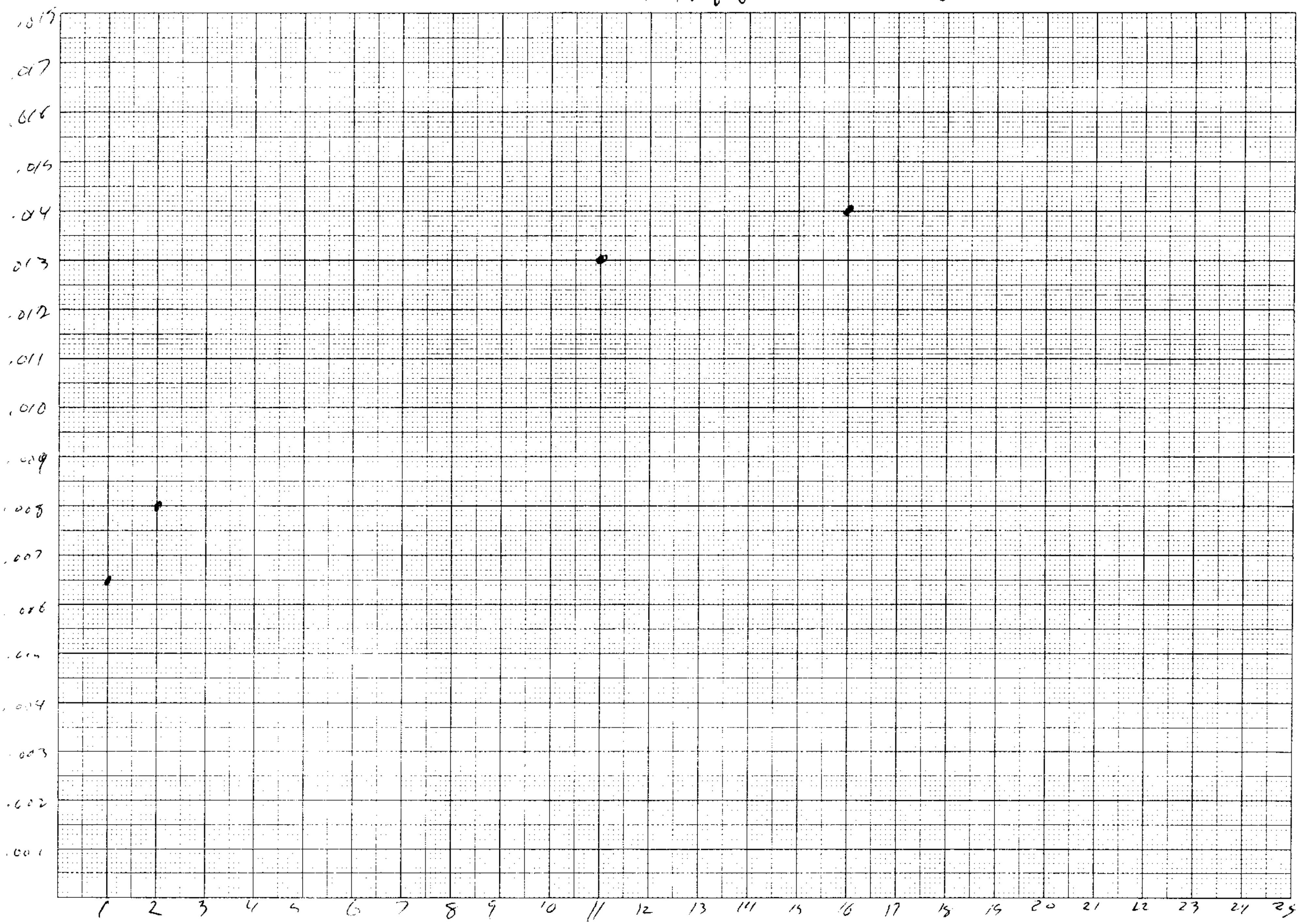
30 days = 43,200 min

6.9 days

69 days

Sample #2
STATION #1
G-10

A vs t G10 #2



.018
.017
.016
.015
.014
.013
.012
.011
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

Packer Eng 6-10-4

.624 x .244 x .385

$\sigma = 19{,}200$ psi

$E_0 = 1.5 \times 10^6$

$E_1 = 2.1 \times 10^6$

$n = .040$

$$n = \frac{\log\left(\epsilon - \frac{\sigma}{E_0}\right) - \log\left(\frac{\sigma}{E_1}\right)}{\log t}$$

$$n = \frac{\log(13.216 \times 10^{-3}) - \log\left(\frac{19200}{2.1 \times 10^6}\right)}{\log(10{,}000)}$$

$$n = \frac{\log(13.216 \times 10^{-3}) - \log(9.1429 \times 10^{-3})}{\log(10{,}000)}$$

$$n = \frac{-1.8789 + 2.0389}{4}$$

$$n = \frac{.16}{4}$$

$n = .04$

[illegible] could be a [illegible] and [illegible] intercept [illegible] 6-10-[illegible] .076 [illegible] [illegible] .018 6-10-[illegible] intercept

[illegible]

Packer Eng. G-11-3

$.624 \times .247 \times .366$

$\sigma = 19{,}200$ psi

$E_0 = 1.5 \times 10^6$

$E_1 = 1.46 \times 10^6$

$m = .03$

$$\log\left(\epsilon - \frac{\sigma}{E_0}\right) = \log\frac{\sigma}{E_1} + n \log t$$

$$n = \frac{\log\left(\epsilon - \frac{\sigma}{E_0}\right) - \log\frac{\sigma}{E_1}}{\log t}$$

log t = 5 intercept

13.15 X 10^{-3} log t = 0 intercept

$$n = \frac{\log(18.57 \times 10^{-3}) - \log\frac{19200}{1.46 \times 10^6}}{\log(100{,}000)}$$

$$n = \frac{-1.7311 - (-1.8811)}{5}$$

$$n = .15/5$$

$$n = .03$$

Packer Eng   laminate

$.632 \times .252 \times .430$

$\sigma = 19{,}200$ psi

$E_0 = 2.0 \times 10^6$

$E_1 = 1.97 \times 10^6$

$n = .030$

$$n = \frac{\log\left(\epsilon - \frac{\sigma}{E_0}\right) - \log\left(\frac{\sigma}{E_1}\right)}{\log t}$$

$$n = \frac{\log(13.767 \times 10^{-3}) - \log\left(\frac{19200}{1.97 \times 10^6}\right)}{\log 100{,}000}$$

$$n = \frac{\log(13.77 \times 10^{-3}) - \log(9.746 \times 10^{-3})}{5}$$

[illegible] slopes
to and check
with the graph

$$n = \frac{-1.8612 + 2.0112}{5}$$

$$n = \frac{.15}{5}$$

$n = .03$

K+E LOGARITHMIC 3 x 5 CYCLES
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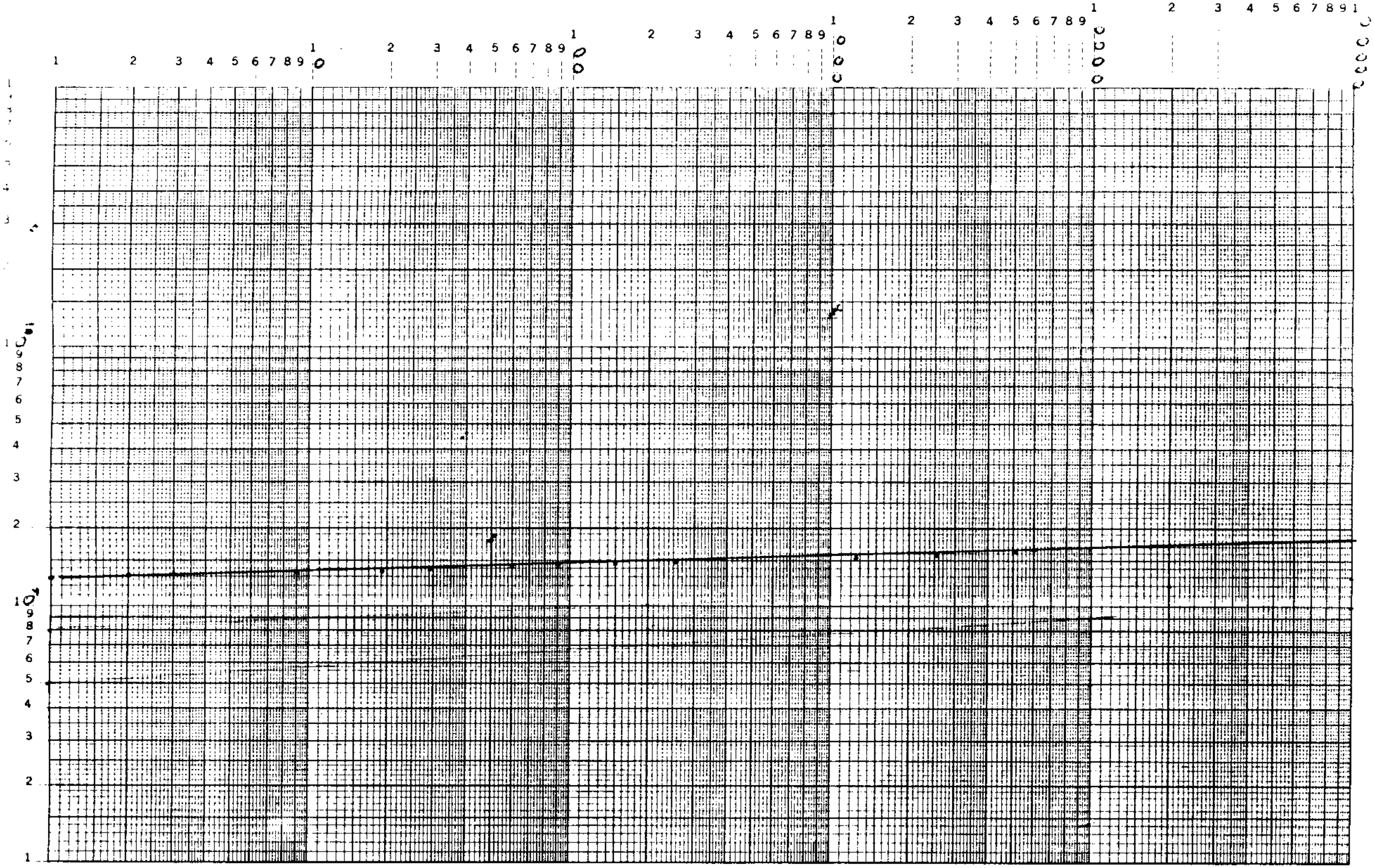
46 7520



$n = 0.030$

$E_1 = 1.476 \times 10^6$ psi

Packer Eng   6-10-3

.624 x .244 x .385 "

$\sigma = 19{,}200$ psi

$E_0 = 1.5 \times 10^6$

$E_1 = 2.28 \times 10^6$

$n = .051$

$$n = \frac{\log\left(\epsilon - \frac{\sigma}{E_0}\right) - \log\left(\frac{\sigma}{E_1}\right)}{\log t}$$

$$n = \frac{\log(13.471 \times 10^{-3}) - \log\left(\frac{19200}{2.28 \times 10^6}\right)}{\log 10{,}000}$$

$$n = \frac{-1.8706 \quad \log(8.42 \times 10^{-3})}{4}$$

$$n = \frac{-1.8706 \quad -(-2.0746)}{4}$$

$n = .204$

$n = .051$

$G-10-3$

$\sigma = 19{,}200$
$E_0 = 1.5 \times 10^6$
$E_1 = 2.28 \times 10^6$
$n = .051$

$$\epsilon = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} t^n$$

$$\epsilon = \frac{19200}{1.5 \times 10^6} + \frac{19200}{2.28 \times 10^6} t^{.051}$$

$$\epsilon = (12.8 + 8.42 \times t^{.051})10^{-3}$$

		ϵ - "assumption"
$t = 1$	$\epsilon = (12.8 + 8.42) \times 10^{-3}$ $\epsilon = 21.22 \times 10^{-3}$	.02052
$t = 2$	$\epsilon = (12.8 + 8.42 \times 1.036) \times 10^{-3}$ $\epsilon = 21.52 \times 10^{-3}$	.02050
$t = 5$	$\epsilon = (12.8 + 8.42 \times 1.086) \times 10^{-3}$ $\epsilon = 21.94 \times 10^{-3}$	.02054
$t = 10$	$\epsilon = (12.8 + 8.42 \times 1.125) \times 10^{-3}$ $\epsilon = 22.27 \times 10^{-3}$	.02053
$t = 20$	$\epsilon = (12.8 + 8.42 \times 1.165) 10^{-3}$ $\epsilon = 22.61 \times 10^{-3}$	.02052
$t = 30$	$\epsilon = (12.8 + 8.42 \times 1.189) 10^{-3}$ $\epsilon = 22.81 \times 10^{-3}$	.02053
$t = 50$	$\epsilon = (12.8 + 8.42 \times 1.221) \times 10^{-3}$ $\epsilon = 23.08 \times 10^{-3}$	.02062
$t = 100$	$\epsilon = (12.8 + 8.42 \times 1.265) \times 10^{-3}$ $\epsilon = 23.45 \times 10^{-3}$	.02066
$t = 6022$	$\epsilon = (12.8 + 8.42 \times 6022^{.051}) \times 10^{-3}$ $\epsilon = 25.92 \times 10^{-3}$	.02066

Packer Eng. G-11-2

$.624 \times .247 \times .366$

$\sigma = 19{,}200$ psi

$E_0 = 1.5 \times 10^6$

$E_1 = 1.42 \times 10^6$

$n = .032$

$$\log\left(\epsilon - \frac{\sigma}{E_0}\right) = \log\frac{\sigma}{E_1} + n\log t$$

at $t = 1$ min

$\log t = 0$

$$\log\left(\epsilon - \frac{\sigma}{E_0}\right) = \log\frac{\sigma}{E_1} = \log\frac{19{,}200}{1.42\times10^6} = \log 13.521\times10^{-3} = -1.869$$

$$n = \frac{+\log\left(\epsilon - \frac{\sigma}{E_0}\right) - \log\frac{\sigma}{E_1}}{\log t}$$

$$n = \frac{-\log(13.521\times10^{-3}) + \log(19.54\times10^{-3})}{\log(100{,}000)}$$

log t = 0 intercept

log t = 5 intercept

$$n = \frac{+1.869 + (-1.709)}{5}$$

$$n = \frac{+.16}{5}$$

$n = +.032$

total ϵ

$$\left(701 + \frac{\sigma}{E_{room}}\right) - \frac{\sigma}{E_0} = \epsilon_{creep}$$

E_{room} defines at $2 \times E_0$

$$\epsilon = \cancel{\frac{\text{dial gauge}}{15} \times (\text{tenths})}$$

$\therefore$ lever arm = 15 magnification

G-11-2

$\sigma = 19{,}200$ psi $E_0 = 1.5\times10^6$ $E_1 = 1.42\times10^6$ $n = .032$

$$\epsilon = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} t^n$$

creep strain + .0128

at $t = 1$ min $\epsilon = \frac{19200}{1.5\times10^6} + \frac{19200}{1.42\times10^6}(1)^{.032}$

$\epsilon = .12.8\times10^{-3} + 13.52\times10^{-3}\times1$

$\epsilon = 26.32\times10^{-3} = .02632$ in/in $\longrightarrow$ .026301

at $t = 100{,}000$ $\epsilon = 12.8\times10^{-3} + 13.52\times10^{-3}(100{,}000)^{.032}$

$\epsilon = (12.8 + 13.52\times1.445)\times10^{-3}$

$\epsilon = (12.8 + 19.54)\times10^{-3}$

$\epsilon = 32.34\times10^{-3} = .03234$ inch

at $t = 19860$ $\epsilon = (12.8 + 13.52\times19860^{.032})\times10^{-3}$

$\epsilon = (12.8 + 13.52\times1.373)\times10^{-3}$

$\epsilon = (12.8 + 18.56)\times10^{-3}$

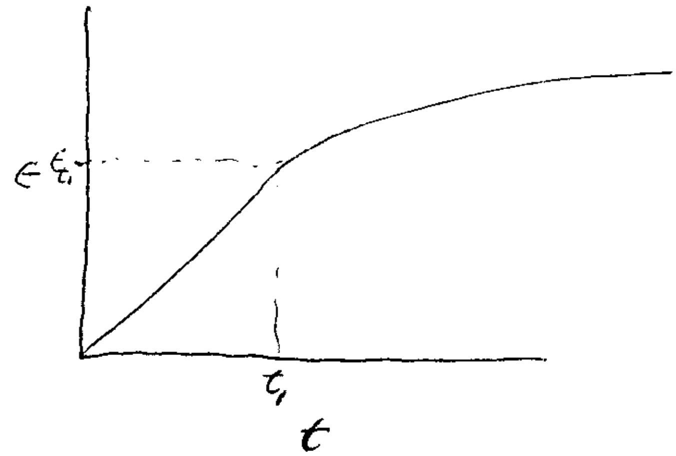
$\epsilon = 31.36\times10^{-3} = .03136 \longrightarrow .031301$

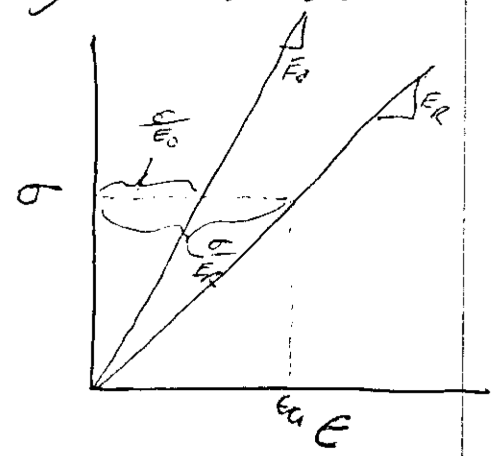
TOTAL STRAIN = ELASTIC STRAIN + CREEP STRAIN

$$\epsilon = \epsilon_0 + \epsilon_1 t^n$$

σ_c = constant for $t \geq t_1$
$\sigma_t = Rt$ for $t < t_1$

Now for a ramped loading situation





Let ϵ_{ARC} = "as read creep" = strain occurring after time t_1

$$\epsilon = \epsilon_{t_1} + \epsilon_{ARC} = \epsilon_0 + \epsilon_1 t^n$$

$$\epsilon = \frac{\sigma_c}{E_R} + \epsilon_{ARC} = \epsilon_0 + \epsilon_1 t^n$$

$$\epsilon - \epsilon_0 = \frac{\sigma_c}{E_R} - \epsilon_0 + \epsilon_{ARC} = \epsilon_1 t^n$$

$$\epsilon - \epsilon_0 = \left(\frac{\sigma_c}{E_R} - \frac{\sigma_c}{E_0}\right) + \epsilon_{ARC} = \epsilon_1 t^n$$

$$\ln(\epsilon - \epsilon_0) = \ln\left[\left(\frac{\sigma_c}{E_R} - \frac{\sigma_c}{E_0}\right) + \epsilon_{ARC}\right] = \ln \epsilon_1 + n \ln t$$

which is the equation of a straight line where n is the slope and $\ln \epsilon_1$ is the value at $t = 1$ unit

Caulfield assumes 1.5×10^6 psi $= E_0 = 2 E_R$

then $\frac{\sigma_c}{E_R} - \frac{\sigma_c}{E_0} = \frac{\sigma_c}{\frac{1}{2}E_0} - \frac{\sigma_c}{E_0} = 2\frac{\sigma_c}{E_0} - \frac{\sigma_c}{E_0} = \frac{\sigma_c}{E_0}$

and since $\sigma_c = 19{,}200$ psi $\frac{\sigma_c}{E_0} = .0128$

$$\ln(\epsilon - \epsilon_0) = \ln(\epsilon_{ARC} + .0128) = \ln \epsilon_1 + n \ln t$$

note: Caulfield's t in min and log instead of ln

$$\log_A(C) = \log_A(B)\log_B(C)$$

$\log_e(t^n) = \log_e(t)\log_t(t^n)$

$\log_e(t^n) = \log_e(t)\ n$

$\ln t^n = n \ln t$

$\log_{10}(t^n) = \log_{10}(t)\log_t(t^n)$

$\log_{10}(t^n) = \log_{10}(t)\ n$

$\log t^n = n \log t$

$l = .366$
$A = (.624)(.247)$

for G 11 He plots $\log(\epsilon_{ARC} + .0128)$ vs $\log t$

ϵ_{ARC} = "as read creep"

$\epsilon_{ARC} + .0128$ = "creep strain"

$l = .385$
$A = (.624)(.244)$

for G10 He plots $\log(\frac{A}{5.7} + .0076)$ vs $\log t$

$\frac{A}{5.7} + .0076$ = "creep strain"

A is an unidentified number that may be a dial gauge reading on the end of the force lever if so then ~~creep~~ strain $= \frac{\Delta l}{l} = \frac{A/r}{l} = \frac{A}{rl}$

r = ratio of lever arms

$l = .385$ = sample height then l would be 14.8

$l = .430$
$A = (.632)(.252)$

for laminates